

Solar-like oscillations in cluster stars*

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We present a brief overview of the history of attempts to obtain a clear detection of solar-like oscillations in cluster stars, and discuss the results on the first clear detection, which was made by the Kepler Asteroseismic Science Consortium (KASC) Working Group 2.

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1 Introduction

Star clusters are extremely important in stellar astrophysics. Most stars form in open clusters, many of which disperse into the diversity of field stars in the interstellar medium. Understanding the formation and evolution of cluster stars is therefore important for achieving a comprehensive theory of stellar evolution. Stars in a cluster are thought to be formed coevally, from the same interstellar cloud of gas and dust. Each cluster member is therefore expected to have some properties in common (age, composition, distance), which strengthens our ability to constrain our stellar models when tested against an ensemble of cluster stars, especially for asteroseismic analyses (Gough & Novotny 1993). Asteroseismology has the capability to probe the interior of stars and hence help us understand the fundamental physi-

cal process that govern stellar structure and evolution (e.g., Christensen-Dalsgaard 2002). In particular, the detection of solar-like oscillations provide many modes, which each carrying unique information about the stellar interior. Stars that potentially exhibit solar-like oscillations, covering most stars that we see, are cooler than the red edge of the classical instability strip, and have a convection zone near the surface (necessary for the excitation of the modes). Solar-like oscillations are reasonably well described by current theory, giving us some confidence that we can use them as tools to understand stellar physics, and hopefully also to learn more about the more subtle aspects of the oscillations themselves. Combining asteroseismic analysis of solar-like oscillations with the study of cluster stars has therefore been a long-sought goal.

* Data from *Kepler*

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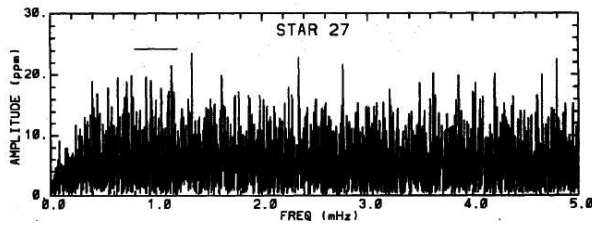


Fig. 1 Amplitude spectrum (high-pass filtered) of one of the stars targeted by Gilliland et al. (1993). The horizontal line marks the expected location of the oscillations.

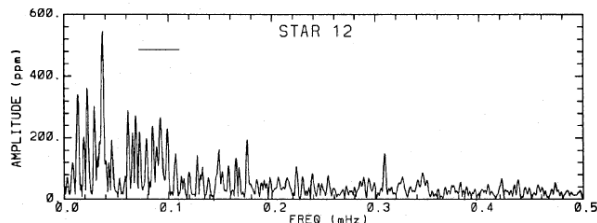


Fig. 2 Amplitude spectrum of red giant star observed by Gilliland et al. (1993). Horizontal line marks the expected location of the oscillations.

2 Previous attempts

Kepler is certainly not the first attempt to detect solar-like oscillations in cluster stars. A quick (and hence incomplete) perusal of the history of previous attempts to detect solar-like oscillations in open and globular clusters shows that several attempts were made to detect oscillations since the early 1990s. Among the most ambitious was that of Gilliland et al. (1993), who used 4-m class telescopes to target the stars in the open cluster M67 at the cluster turn-off in a multi-site campaign that lasted one week. While an impressively low noise level was obtained, the data did not reveal the clear detection of stellar oscillations (Figure 1). However, a red giant star that happened to be in the field did show intriguing evidence of excess power in the expected frequency range (Figure 2). Unfortunately, the length of the time series did not allow individual modes to be resolved for such an evolved star with much smaller frequency separations between modes. A clear detection remained elusive, as oscillations could not be distinguished from the rising background towards low frequency.

Inspired by Gilliland's results, Stello et al. (2007) targeted specifically the red giants in M67 during a 6-week long multi-site campaign of 1–2m class telescopes. Strong evidence for excess power was found in a number of stars, but no unambiguous detection of the solar-like pattern of equally spaced modes was claimed by the authors (Figure 3).

In parallel, several attempts to detect oscillations in globular clusters were carried out. From the ground, Frandsen et al. (2007) aimed at the red giants in M4, which delivered lower limits on amplitudes, indicating that the low metallicity of M4 could have the effect of lowering the oscillation ampli-

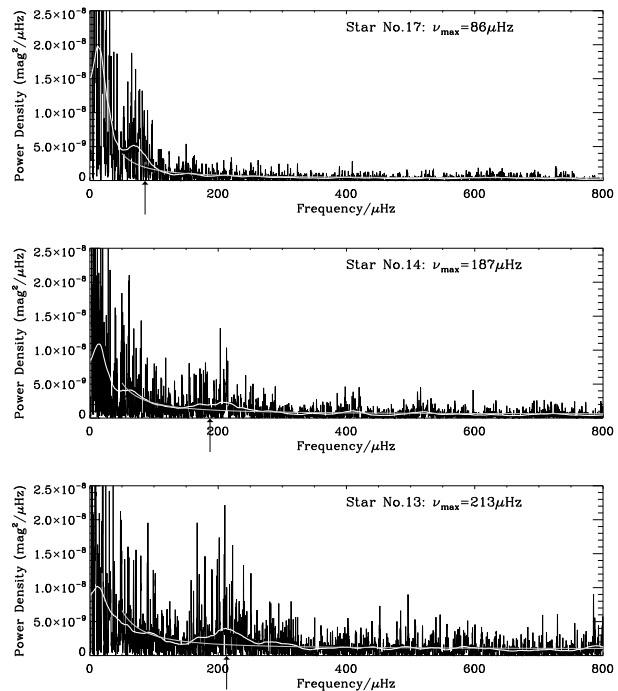


Fig. 3 Power spectra of three red giant stars observed by Stello et al. (2007). Black arrow marks the location of the oscillations expected from scaling the solar value.

tudes. Again, detection was hindered by long-term stability not being high enough and varying data quality resulting in strong aliasing in the weighted amplitude spectra. Slightly more successful were the efforts using the *Hubble Space Telescope* by Edmonds & Gilliland (1996); Stello & Gilliland (2009). In the former study, clear variation was found in a large number of red giants in 47 Tuc, but the low frequency resolution provided by the 40-hour time series did not allow the authors to establish this as solar-like oscillations. The later study was aimed at the red giants in the extremely metal poor NGC 6397, using archival data originally obtained to detect the cluster's faint white dwarf population. The far from ideal data of highly saturated photometry of the red giants meant that only one star showed good evidence for oscillations, with excess power at the right frequency range and amplitude. Despite the 27-day long time series, this fell just short for an unambiguous detection of equally spaced frequencies in this highly evolved asymptotic giant branch star.

The main conclusion from these previous efforts is that dedicated space-based missions are required to achieve the ultra-high precision photometry and long-term stability in order to detect solar-like oscillations in clusters with such accuracy that they will be useful for asteroseismic analysis.

We note that in addition to the previous marginal detections, these campaigns resulted in firm detection of oscillations in a number of classical pulsators that exhibit much large amplitude than solar-like oscillations (see e.g. Bruntt 2007 and references therein).

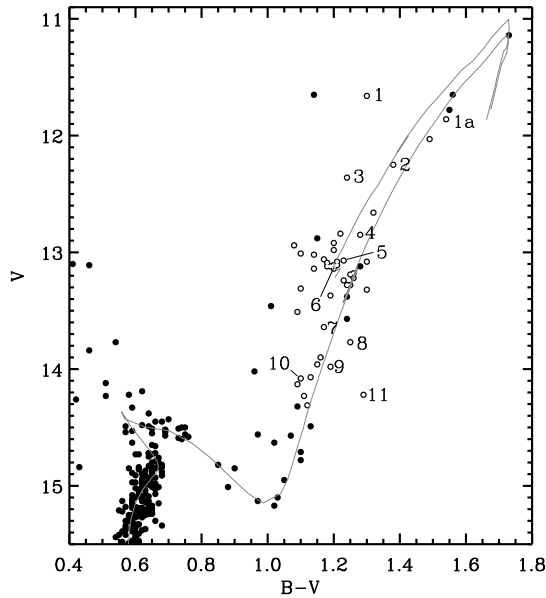


Fig. 4 HR-diagram of NGC 6819. Empty symbols mark those where a detection of solar-like oscillations was reported by Stello et al. (2010).

3 First results from *Kepler*

Kepler has a unique capability to overcome the shortcomings that have limited previous efforts aimed at stellar clusters. Both quality and quantity of the *Kepler* data outshine that of early explorations by several orders of magnitude, and it will undoubtedly be the front runner for cluster seismology in the next 5–10 years.

As reported by Stello et al. (2010), the first month of *Kepler* data already revealed clear detection of solar-like oscillations in a large sample of red giant stars in the open cluster NGC 6819 (see also Gilliland et al. 2010). Based on the spacecrafts so called long-cadence mode, which provides a time averaged exposure every 29.4 minutes, detection was reported in 47 red giant stars that range almost from the bottom to the tip of the red giant branch (Figure 4). We saw periodicity in the light curves that span about a factor of 100, corresponding to a factor of ~ 10 in radius. Two sample light curves are shown in Figure 5. Power spectra of the stars marked with numbers in Figure 4 are shown in Figure 6. Panels are sorted according to apparent magnitude (brightest at the top), which for a cluster is indicative of luminosity. One noticeable result is that not all stars with high membership probability from radial velocity surveys (see Hole et al. 2009) follow the expected monotonic trend of increasing frequency of the oscillations (and decreasing amplitude) for decreasing luminosity. We indicate the expected frequency location with an arrow for stars that seem to behave strangely compared to the classical scaling relations for the amplitude and the frequency of maximum power (e.g. Kjeldsen & Bedding 1995). Possible explana-

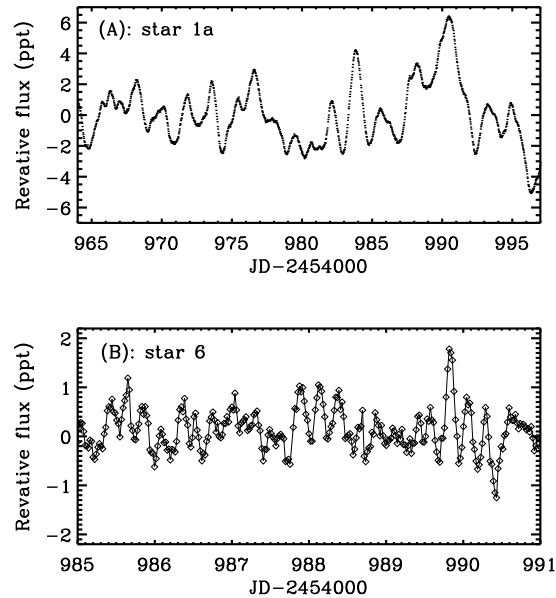


Fig. 5 *Kepler* time series for two red giants in NGC 6819. Numbers refer to the numbering in Figure 4. Note the different time scale of the variation. Photometry and isochrone is of Hole et al. (2009) and Marigo et al. (2008), respectively.

Table 1 Open clusters in *Kepler* field

Cluster	Age Gyr	[Fe/H]	M_{turnoff} M_{\odot}
NGC 6866	~ 0.4	~ -0.1	~ 1.7
NGC 6811	~ 1.0	~ -0.07	~ 1.5
NGC 6819	~ 2.5	~ -0.05	~ 1.3
NGC 6791	~ 8.5	$\sim +0.4$	~ 1.0

Values are from Grundahl et al. (2008) (NGC 6791),

Hole et al. (2009) (NGC 6819), Loktin & Matkin (1994) (NGC 6866)

and unpublished work by Meibom.

tions for this behaviour are that these “odd” stars are not members, or that they have unusual evolution histories.

Stello et al. (2010) were further able to measure the amplitudes of the modes using the method by Kjeldsen et al. (2009), assuming the relative amplitudes of the modes of different spherical degree was the same as for the Sun. From this we could test the L/M scaling relation (Kjeldsen & Bedding 1995; Samadi et al. 2007), and found that $(L/M)^{0.7}/T_{\text{eff}}^2$ provided the best match to the data.

For further details on what is reported here, we refer to the source paper of Stello et al. (2010).

4 Future

There are four open clusters in *Kepler*’s field of view. They span a range in metallicity and age, which brackets the solar values, and are therefore ideal for testing our current models of stellar evolution (Table 1).

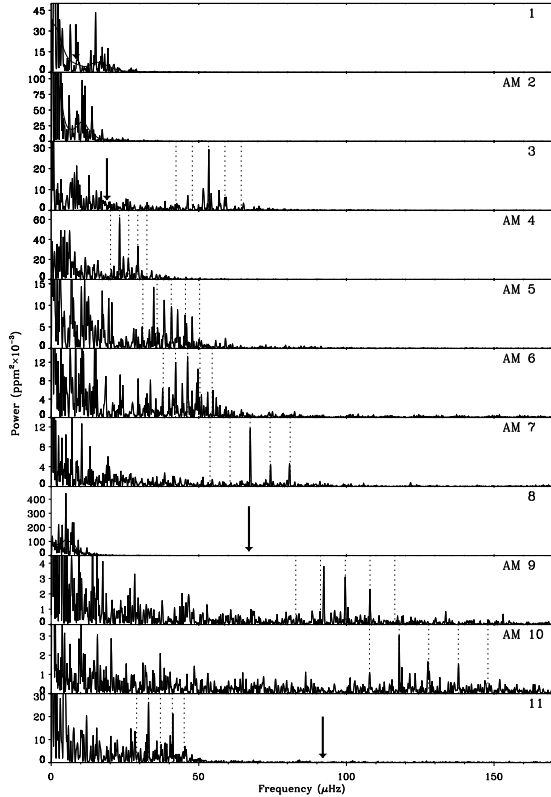


Fig. 6 Power spectra of 11 stars marked in Figure 4, which are representative for the entire sample. ‘AM’ indicates that the star is an asteroseismic member (i.e. observation agrees with scaling relations). Dashed lines show the measured large frequency separation. For stars where the large separation could not be determined (no dashed lines), we localised the power excess from the hump of power in the smoothed power spectrum (solid black curve). The arrows indicate the expected location of the excess power for stars where observations do not agree with expectation.

In Figure 7 we show $\log(g)$ vs T_{eff} for a representative sample of the stars in *Kepler*’s field of view together with the representative isochrones for the four open clusters that are targets in our future asteroseismic analyses.

For NGC 6819 we expect to achieve a signal-to-noise level for the turn-off stars that after 3.5 years of data matches what we see in the bottom panels of Figure 6. This will provide detection in up to 100 stars ranging stellar evolution from the main sequence F stars to the asymptotic giant branch including M giants, as well as a number of blue stragglers. This will potentially provide unprecedented tests of state-of-the-art stellar evolution models.

In NGC 6791 we already see evidence for power in the red giants, and expect firm detections for all stars on this highly populated red giant branch, with unique potential for testing intrinsic variation among practically identical stars.

The two younger clusters NGC 6811 and NGC 6866 are less populated but provide the opportunity to investigate

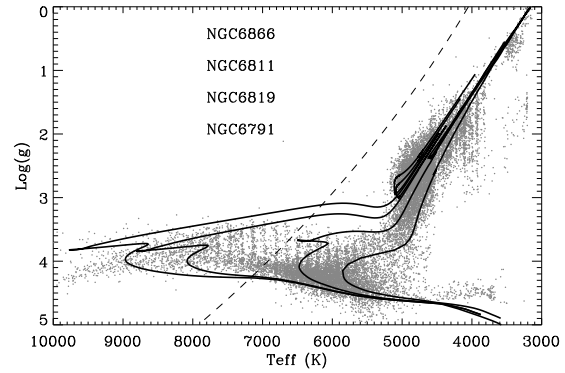


Fig. 7 $\log(g)$ vs T_{eff} for stars in *Kepler*’s field of view. We represent the four open clusters by suitable isochrones. The order in which we have plotted the cluster names corresponds to their turn-off stars, with NGC 6866 having the hottest (heaviest) turn-off stars and NGC 6791 the coolest (lightest). The dashed line indicates the red edge of the classical instability strip.

classical pulsators in great detail. NGC 6811 also contains a few He-core burning red giants.

The combination of results from all four clusters promises great prospects for testing asteroseismic scaling relations on distinct stellar populations that span a large range in stellar age and brackets the solar metallicity.

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